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## Measurement of the Lifetime of the Doubly Charmed Baryon $\Xi_{cc}^{++}$

LHCb Collaboration ; Bernet, R ; Müller, K ; Serra, N ; Steinkamp, O ; Straumann, U ; Vollhardt, A ;  
et al

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Measurement of the Lifetime of the Doubly Charmed Baryon  $\Xi_{cc}^{++}$ R. Aaij *et al.*<sup>\*</sup>  
(LHCb Collaboration)

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The first measurement of the lifetime of the doubly charmed baryon  $\Xi_{cc}^{++}$  is presented, with the signal reconstructed in the final state  $\Lambda_c^+ K^- \pi^+ \pi^+$ . The data sample used corresponds to an integrated luminosity of  $1.7 \text{ fb}^{-1}$ , collected by the LHCb experiment in proton-proton collisions at a center-of-mass energy of 13 TeV. The  $\Xi_{cc}^{++}$  lifetime is measured to be  $0.256_{-0.022}^{+0.024}(\text{stat}) \pm 0.014(\text{syst}) \text{ ps}$ .

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The quark model of hadrons predicts the existence of weakly decaying baryons that contain two beauty or charm quarks, and are therefore referred to as doubly heavy baryons. Such states provide a unique system for testing models of quantum chromodynamics (QCD), the theory that describes the strong interaction. In the quark model, the doubly charmed baryon  $\Xi_{cc}$  forms an isodoublet, consisting of the  $\Xi_{cc}^{++}$  and  $\Xi_{cc}^{+}$  baryons with quark content  $ccu$  and  $ccd$ , respectively. Predictions for the  $\Xi_{cc}^{++}$  lifetime span the range from 50 to 250 fs, while the  $\Xi_{cc}^{+}$  lifetime is expected to be three to four times larger, from 200 to 1050 fs [1–10]. The predicted larger  $\Xi_{cc}^{+}$  lifetime is due to the destructive Pauli interference of the charm-quark decay products and the valence (up) quark in the initial state, whereas the  $\Xi_{cc}^{++}$  lifetime is shortened due to an additional contribution from  $W$ -exchange between the charm and down quarks [1–10]. Charge-conjugate processes are implied throughout this Letter.

The SELEX Collaboration [11,12] reported the observation of the  $\Xi_{cc}^{+}$  baryon in the final states  $\Lambda_c^+ K^- \pi^+$  and  $p D^+ K^-$ , with a measured mass of  $3518.7 \pm 1.7 \text{ MeV}/c^2$ . Its lifetime was found to be less than 33 fs at the 90% confidence level. However, the signal has not been confirmed in searches performed at the FOCUS [13], BABAR [14], Belle [15], and LHCb [16] experiments. Recently, the LHCb Collaboration observed a resonance in the  $\Lambda_c^+ K^- \pi^+ \pi^+$  mass spectrum at a mass of  $3621.40 \pm 0.78 \text{ MeV}/c^2$  [17], which is consistent with expectations for the  $\Xi_{cc}^{++}$  baryon (see, e.g., Ref. [18]). The difference in masses between the two reported states,  $103 \pm 2 \text{ MeV}/c^2$ , is much larger than the few  $\text{MeV}/c^2$  expected by the breaking of isospin symmetry [19–21], and that is observed

in all other isodoublets. While the resonance seen in the  $\Lambda_c^+ K^- \pi^+ \pi^+$  mass spectrum by LHCb is consistent with being the  $\Xi_{cc}^{++}$  baryon, a measurement of its lifetime is critical to establish its nature. The lifetime is also a necessary ingredient for theoretical predictions of branching fractions of  $\Xi_{cc}$  decays, and can offer insight into the interplay between strong and weak interactions in these decays.

This Letter reports the first measurement of the  $\Xi_{cc}^{++}$  lifetime, with the  $\Xi_{cc}^{++}$  baryon reconstructed through the decay chain  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ ,  $\Lambda_c^+ \rightarrow p K^- \pi^+$ . The data sample used, the same as in Ref. [17], corresponds to an integrated luminosity of  $1.7 \text{ fb}^{-1}$ , collected by the LHCb experiment in proton-proton collisions at a center-of-mass energy of 13 TeV. Since the combined reconstruction and selection efficiency varies as a function of the decay time, the decay-time distribution is measured relative to that of a control mode with similar topology and known lifetime [22,23],  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ . This technique, used in a number of lifetime measurements at LHCb [22,24–31], leads to a reduced systematic uncertainty as it is only sensitive to the ratio of the decay-time acceptances.

The LHCb detector [32,33] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector elements that are particularly relevant to this analysis are a silicon-strip vertex detector [34] surrounding the  $pp$  interaction region that allows  $c$  and  $b$  hadrons to be identified from their characteristically long flight distance, a tracking system [35], placed upstream and downstream of a dipole magnet, that provides a measurement of momentum,  $p$ , of charged particles, and two ring-imaging Cherenkov detectors [36] that are able to discriminate between different species of charged hadrons. The magnetic field polarity can be reverted periodically throughout the data-taking. The online event selection is performed by a trigger [37], which consists of a hardware stage, based on information from the calorimeter and muon systems [38,39], followed by a software stage, which applies a full event reconstruction incorporating near-real-time alignment and calibration of

<sup>\*</sup>Full author list given at the end of the Letter.

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the detector [40]. The output of the reconstruction performed in the software trigger [41] is used as input to the present analysis.

Samples of simulated  $pp$  collisions are generated using PYTHIA [42] with a specific LHCb configuration [43]. A dedicated generator, GENXICC2.0 [44], is used to simulate the production of the  $\Xi_{cc}^{++}$  baryon. Decays of hadrons are described by EVTGEN [45], in which final-state radiation is simulated using PHOTOS [46]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [47] as described in Ref. [48].

Candidate  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  decays are reconstructed and selected with a multivariate selector following the same procedure as used in the previous analysis [17], except for two additional selection criteria. The first requires that the events are selected, at the hardware-trigger level, either by large transverse energy deposits in the calorimeter from the decay products of the  $\Xi_{cc}^{++}$  candidate or by activity in the calorimeter or muon system from particles other than the  $\Xi_{cc}^{++}$  decay products. This requirement removes events for which the efficiency cannot be determined precisely. The second is a requirement on the reconstructed decay time of the  $\Xi_{cc}^{++}$  candidates,  $t$ , which must lie in the range 0.1–2.0 ps, where the lower limit on  $t$  is imposed to avoid biases from resolution effects. Candidate  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$  decays are reconstructed and selected in exactly the same way as  $\Xi_{cc}^{++}$  decays, except that the allowed invariant-mass range is centred around the  $\Lambda_b^0$  mass and both negatively charged  $\Lambda_b^0$  decay products are required to be identified as pions. The same hardware and software trigger criteria are applied to both  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  candidates.

To obtain better resolution, the invariant mass of a candidate is calculated as

$$m = M(\Lambda_c^+ h \pi \pi) - M([p K^- \pi^+]_{\Lambda_c^+}) + M_{\text{PDG}}(\Lambda_c^+), \quad (1)$$

where  $h \pi \pi$  indicates  $K^- \pi^+ \pi^+$  ( $\pi^- \pi^+ \pi^-$ ) for  $\Xi_{cc}^{++}$  ( $\Lambda_b^0$ ) candidates,  $M(\Lambda_c^+ h \pi \pi)$  is the invariant mass of the  $\Xi_{cc}^{++}$  or  $\Lambda_b^0$  candidate,  $M([p K^- \pi^+]_{\Lambda_c^+})$  is the invariant mass of the  $\Lambda_c^+$  candidate, and  $M_{\text{PDG}}(\Lambda_c^+)$  is the known value of the  $\Lambda_c^+$  mass [23]. The distributions of the mass  $m$  of selected  $\Lambda_c^+ K^- \pi^+ \pi^+$  and  $\Lambda_c^+ \pi^- \pi^+ \pi^-$  candidates are shown in Fig. 1. Unbinned extended maximum-likelihood fits to these distributions are performed as in Ref. [17], with the signal described by the sum of a Gaussian function and a double-sided Crystal Ball function [49], and the background parametrized by a second-order Chebyshev polynomial. The same fit models are used for both the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  samples, but with different resolution parameters. Signal yields of  $304 \pm 35$   $\Xi_{cc}^{++}$  and  $3397 \pm 119$   $\Lambda_b^0$  decays are obtained. The small decrease in the  $\Xi_{cc}^{++}$  yield compared with the value of  $313 \pm 33$  reported in Ref. [17] is due to the two additional selection requirements described above.

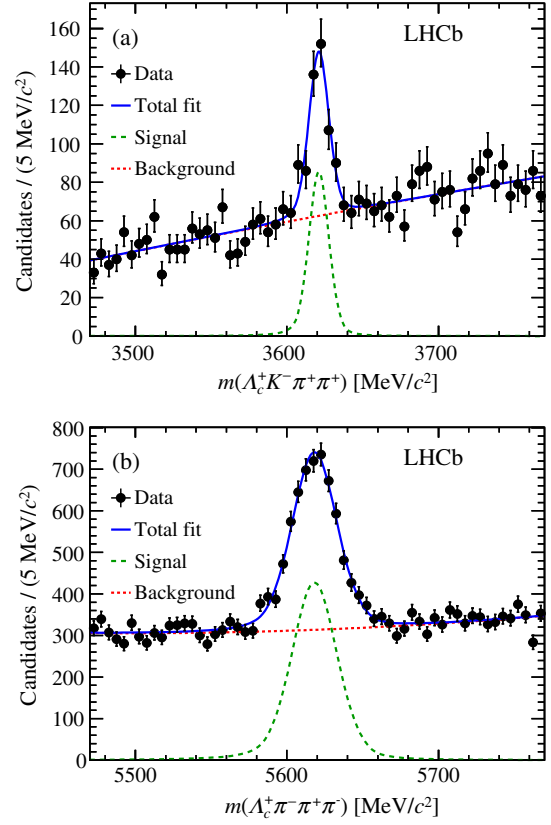


FIG. 1. Invariant-mass distributions of (a)  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  and (b)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$  candidates, with fit results shown.

The decay time of  $\Xi_{cc}^{++}$  or  $\Lambda_b^0$  candidates is computed with a kinematic fit [50] in which the momentum vector of the candidate is required to be aligned with the line joining the production and decay vertices. The decay-time resolution, determined from simulation, is 63 fs (32 fs) for the  $\Xi_{cc}^{++}$  ( $\Lambda_b^0$ ) decay, which is much less than the  $\Xi_{cc}^{++}$  ( $\Lambda_b^0$ ) lifetime and has negligible dependence on the decay time within the current precision. The normalized decay-time distributions of the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  baryons are shown in Fig. 2, where the background contributions have been subtracted according to the fit results shown in Fig. 1 using the *sPlot* technique [51].

The decay-time acceptance is defined as the ratio between the reconstructed and the generated decay-time distributions, and is determined with samples of simulated events containing  $\Xi_{cc}^{++}$  ( $\Lambda_b^0$ ) decays, in which the  $\Xi_{cc}^{++}$  ( $\Lambda_b^0$ ) lifetime is set to 0.333 ps (1.451 ps), as shown in Fig. 3. This decay-time acceptance, which is described by a histogram in this analysis, takes into account the reconstruction efficiency, as well as the bin migration effect caused by the decay-time resolution. A potential bias in the relative decay-time acceptance due to the assumed lifetimes is considered a source of systematic uncertainty. The simulated  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  decays are weighted to match their observed transverse-momentum

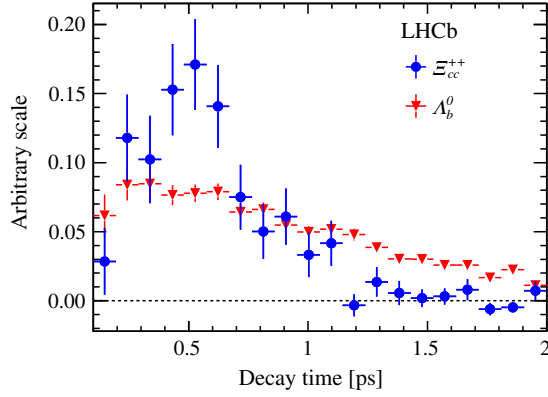


FIG. 2. Background-subtracted decay-time distributions of (dots)  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  and (triangles)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$  candidates after the selection, not corrected for decay-time acceptance.

distributions in data. The difference between the  $\Xi_{cc}^{++}$  or  $\Lambda_b^0$  decay-time acceptances is mainly due to the larger  $\Lambda_b^0$  mass, which results in higher momentum of the decay products and larger opening angles in the decay. An exponential function is fitted to the background-subtracted and acceptance-corrected decay-time distribution of  $\Lambda_b^0$  candidates, and a lifetime of  $1.474 \pm 0.077$  ps is obtained, where the uncertainty is statistical only. This is consistent with the known value  $1.470 \pm 0.010$  ps [23], and validates that the detector simulation correctly reproduces the decay-time acceptance.

The  $\Xi_{cc}^{++}$  lifetime is measured by performing a weighted, unbinned maximum-likelihood fit [52] to the decay-time distribution of the selected  $\Xi_{cc}^{++}$  sample. Each candidate is assigned a signal weight for background subtraction, which is computed using its invariant mass  $m$  as the discriminating variable following the *sPlot* technique [51]. The probability density function describing the decay-time distribution of the  $\Xi_{cc}^{++}$  signal candidates, denoted by  $f_{\Xi_{cc}^{++}}(t)$ , is defined as

$$f_{\Xi_{cc}^{++}}(t) = H_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}(t)}{\epsilon_{\Lambda_b^0}(t)} \times \exp\left(\frac{t}{\tau(\Lambda_b^0)} - \frac{t}{\tau(\Xi_{cc}^{++})}\right), \quad (2)$$

where  $H_{\Lambda_b^0}(t)$  is the background-subtracted decay-time distribution of the  $\Lambda_b^0$  control channel,  $\epsilon_{\Xi_{cc}^{++}}(t)$  and  $\epsilon_{\Lambda_b^0}(t)$  are the decay-time acceptance distributions for the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  decays, and  $\tau(\Lambda_b^0) = 1.470 \pm 0.010$  ps is the known value [23] of the  $\Lambda_b^0$  lifetime [22]. Here  $H_{\Lambda_b^0}(t)$ ,  $\epsilon_{\Xi_{cc}^{++}}(t)$ , and  $\epsilon_{\Lambda_b^0}(t)$  are the histograms shown in Figs. 2 and 3. The binning scheme is chosen to minimize the systematic uncertainty on the lifetime due to the finite bin width. The background-subtracted  $\Xi_{cc}^{++}$  decay-time distribution is shown in Fig. 4 with the fit result superimposed. The only free parameter of the fit is the  $\Xi_{cc}^{++}$  lifetime, which is measured to be  $\tau(\Xi_{cc}^{++}) = 0.256_{-0.022}^{+0.024}$  ps. Here the uncertainties are statistical only, and include contributions due to the limited sizes of the simulated samples (0.007 ps) and of the  $\Lambda_b^0$  sample (0.006 ps). These contributions are estimated with a bootstrapping method [53], where candidates are randomly selected from the original simulated or  $\Lambda_b^0$  samples to form statistically independent samples of pseudodata. The standard deviations of the lifetime measurements obtained in these samples are then taken as the corresponding statistical uncertainty.

Sources of systematic uncertainty on the  $\Xi_{cc}^{++}$  lifetime are summarized in Table I and described below. The effects of the choice of signal and background models are studied by using alternative mass shapes, namely a sum of two Gaussian functions for signal and an exponential function for background. The change in the measured lifetime, 0.005 ps, is assigned as a systematic uncertainty. In the baseline fit, the signal and background mass shapes are assumed to be independent of the decay time. The effect of this assumption is investigated by fitting the invariant-mass distribution of the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  samples in four independent intervals of decay time and recalculating the signal weights

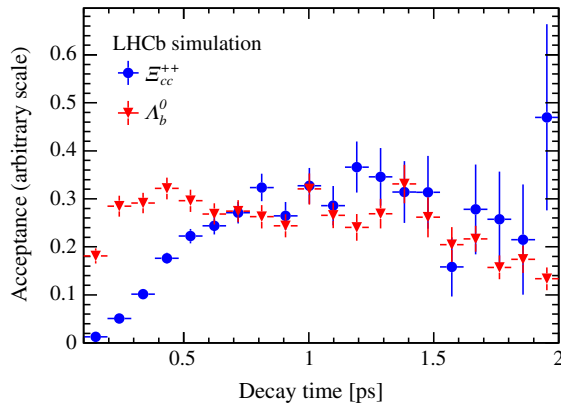


FIG. 3. Decay-time acceptances for (dots)  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  and (triangles)  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$  decays.

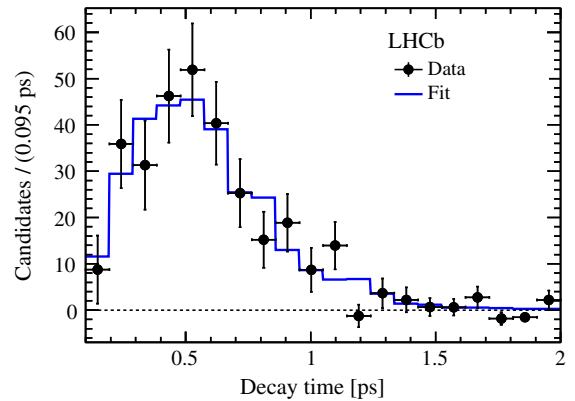


FIG. 4. Background-subtracted decay-time distribution of selected  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  candidates. The rate-averaged fit result across each decay-time bin is shown as the continuous line.



TABLE I. Summary of systematic uncertainties.

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated $\Xi_{cc}^{++}$ lifetime	0.002
$\Lambda_b^0$ lifetime uncertainty	0.001
Sum in quadrature	0.014

based on these fit results. Using these weights in the fit, the  $\Xi_{cc}^{++}$  lifetime changes by 0.004 ps, which is taken as the systematic uncertainty due to the correlation between the mass and decay time. It is found that the measured lifetime depends slightly upon the binning scheme. With the nominal binning, a difference of 0.001 ps with respect to the input lifetime is measured, which is taken as a systematic uncertainty.

The kinematic distributions of the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  signals in the simulation are generally found to be in good agreement with those in data. However, some differences are observed in the output distribution of the multivariate selector. To assess the impact of such differences, the simulation is weighted to match this output distribution in data and the decay-time acceptance is recomputed. The difference between the result from this procedure and the original one is 0.004 ps, which is assigned as the corresponding systematic uncertainty. The simulated  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  and  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$  samples are generated assuming that the decay products are distributed uniformly across the available phase space. The possible effect of intermediate resonances is evaluated by weighting the simulated invariant mass distributions of the three hadrons, i.e.,  $M(K^- \pi^+ \pi^+)$  for  $\Xi_{cc}^{++}$  and  $M(\pi^- \pi^+ \pi^-)$  for  $\Lambda_b^0$  candidates, to match the distributions seen in data. The resulting difference in the measured lifetime, 0.011 ps, is assigned as a systematic uncertainty.

The transverse-energy threshold in the calorimeter hardware trigger varied during data taking, and this variation is not fully described by the simulation. To investigate the influence of this difference, the hardware trigger requirement is applied to the data with a higher (uniform) threshold. The measurement is repeated and the change in the measured lifetime, 0.002 ps, is taken as a systematic uncertainty. The input lifetime used in the simulation for the  $\Xi_{cc}^{++}$  baryon is 0.333 ps. The simulated events are weighted to be distributed according to the measured lifetime and the decay-time acceptance is recomputed. The resulting difference in the measured lifetime, 0.002 ps, is taken as a systematic uncertainty. The  $\Lambda_b^0$  lifetime is precisely known [22,23]. An alternative fit in which  $\tau(\Lambda_b^0)$  is allowed to vary

within its uncertainty leads to a change in the measured  $\Xi_{cc}^{++}$  lifetime of less than 0.001 ps, which is assigned as a systematic uncertainty.

Other systematic effects, including the threshold applied to the multivariate selector, the decay-time resolution, and the uncertainty on the length scale of the vertex detector, are studied and found to be negligible; no systematic uncertainties are assigned for these effects. As further checks, the measured lifetime is compared between subsets of the data, including  $\Xi_{cc}^{++}$  versus  $\Xi_{cc}^{--}$ , opposite LHCb magnet polarities, and different numbers of primary vertices, and is found to be stable. A separate measurement carried out with an alternative method, in which both the  $\Xi_{cc}^{++}$  and  $\Lambda_b^0$  decay-time distributions are binned, gives a consistent result. All sources of systematic uncertainty, listed in Table I, are added in quadrature, and the total systematic uncertainty on the measured  $\Xi_{cc}^{++}$  lifetime is found to be 0.014 ps.

In summary, the  $\Xi_{cc}^{++}$  lifetime is measured using a data sample corresponding to an integrated luminosity of  $1.7 \text{ fb}^{-1}$ , collected by the LHCb experiment in  $pp$  collisions at a center-of-mass energy of 13 TeV, and is found to be

$$\tau(\Xi_{cc}^{++}) = 0.256_{-0.022}^{+0.024}(\text{stat}) \pm 0.014(\text{syst}) \text{ ps}.$$

This is the first measurement of the  $\Xi_{cc}^{++}$  lifetime, which establishes the weakly decaying nature of the recently discovered  $\Xi_{cc}^{++}$  state. The result favors smaller values in the range of the theoretical predictions [1–10]. If the lifetime of the isospin partner state  $\Xi_{cc}^+$  is shorter by a factor of 3 to 4 as predicted [1–10], it would be roughly 60–90 fs. This provides important information to guide the search for the  $\Xi_{cc}^+$  state at the Large Hadron Collider.

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Baranov,<sup>37</sup> R. J. Barlow,<sup>56</sup> S. Barsuk,<sup>7</sup> W. Barter,<sup>56</sup> F. Baryshnikov,<sup>34</sup> V. Batozskaya,<sup>31</sup> B. Batsukh,<sup>61</sup> V. Battista,<sup>43</sup> A. Bay,<sup>43</sup> J. Beddow,<sup>53</sup> F. Bedeschi,<sup>24</sup> I. Bediaga,<sup>1</sup> A. Beiter,<sup>61</sup> L. J. Bel,<sup>27</sup> N. Beliy,<sup>63</sup> V. Bellec,<sup>43</sup> N. Belloli,<sup>20,c</sup> K. Belous,<sup>39</sup> I. Belyaev,<sup>34,42</sup> E. Ben-Haim,<sup>8</sup> G. Bencivenni,<sup>18</sup> S. Benson,<sup>27</sup> S. Beranek,<sup>9</sup> A. Berezhnoy,<sup>35</sup> R. Bernet,<sup>44</sup> D. Berninghoff,<sup>12</sup> E. Bertholet,<sup>8</sup> A. Bertolin,<sup>23</sup> C. Betancourt,<sup>44</sup> F. Betti,<sup>15,42</sup> M. O. Bettler,<sup>49</sup> M. van Beuzekom,<sup>27</sup> I. A. Bezshyiko,<sup>44</sup> S. Bhasin,<sup>48</sup> J. Bhom,<sup>29</sup> L. Bian,<sup>64</sup> S. Bifani,<sup>47</sup> P. Billoir,<sup>8</sup> A. Birnkraut,<sup>10</sup> A. Bizzeti,<sup>17,d</sup> M. Bjørn,<sup>57</sup> M. P. Blago,<sup>42</sup> T. Blake,<sup>50</sup> F. Blanc,<sup>43</sup> S. Blusk,<sup>61</sup> D. Bobulska,<sup>53</sup> V. Bocci,<sup>26</sup> O. Boente Garcia,<sup>41</sup> T. Boettcher,<sup>58</sup> A. Bondar,<sup>38,e</sup> N. Bondar,<sup>33</sup> S. Borghi,<sup>56,42</sup> M. Borisyak,<sup>37</sup> M. Borsato,<sup>41</sup> F. Bossu,<sup>7</sup> M. Boubdir,<sup>9</sup> T. J. V. Bowcock,<sup>54</sup> C. Bozzi,<sup>16,42</sup> S. Braun,<sup>12</sup> M. Brodski,<sup>42</sup> J. Brodzicka,<sup>29</sup> A. Brossa Gonzalo,<sup>50</sup> D. Brundu,<sup>22</sup> E. Buchanan,<sup>48</sup> A. Buonauro,<sup>44</sup> C. Burr,<sup>56</sup> A. Bursche,<sup>22</sup> J. Buytaert,<sup>42</sup> W. Byczynski,<sup>42</sup> S. Cadeddu,<sup>22</sup> H. Cai,<sup>64</sup> R. Calabrese,<sup>16,a</sup> R. Calladine,<sup>47</sup> M. Calvi,<sup>20,c</sup> M. Calvo Gomez,<sup>40,f</sup> A. Camboni,<sup>40,f</sup> P. Campana,<sup>18</sup> D. H. Campora Perez,<sup>42</sup> L. Capriotti,<sup>56</sup> A. Carbone,<sup>15,g</sup> G. Carboni,<sup>25</sup> R. Cardinale,<sup>19,h</sup> A. Cardini,<sup>22</sup> P. Carniti,<sup>20,c</sup> L. Carson,<sup>52</sup> K. Carvalho Akiba,<sup>2</sup> G. Casse,<sup>54</sup> L. Cassina,<sup>20</sup> M. Cattaneo,<sup>42</sup> G. Cavallero,<sup>19,h</sup> R. Cenci,<sup>24,i</sup> D. Chamont,<sup>7</sup> M. G. Chapman,<sup>48</sup> M. Charles,<sup>8</sup> Ph. Charpentier,<sup>42</sup> G. Chatzikonstantinidis,<sup>47</sup> M. Chefdeville,<sup>4</sup> V. Chekalina,<sup>37</sup> C. Chen,<sup>3</sup> S. Chen,<sup>22</sup> S.-G. Chitic,<sup>42</sup> V. Chobanova,<sup>41</sup> M. Chrzasczcz,<sup>42</sup> A. Chubykin,<sup>33</sup> P. Ciambrone,<sup>18</sup> X. Cid Vidal,<sup>41</sup> G. Ciezarek,<sup>42</sup> P. E. L. Clarke,<sup>52</sup> M. Clemencic,<sup>42</sup> H. V. Cliff,<sup>49</sup> J. Closier,<sup>42</sup> V. Coco,<sup>42</sup> J. A. B. Coelho,<sup>7</sup> J. Cogan,<sup>6</sup> E. Cogneras,<sup>5</sup> L. Cojocariu,<sup>32</sup> P. Collins,<sup>42</sup> T. Colombo,<sup>42</sup> A. Comerma-Montells,<sup>12</sup> A. Contu,<sup>22</sup> G. Coombs,<sup>42</sup> S. Coquereau,<sup>40</sup> G. Corti,<sup>42</sup> M. Corvo,<sup>16,a</sup> C. M. Costa Sobral,<sup>50</sup> B. Couturier,<sup>42</sup> G. A. Cowan,<sup>52</sup> D. C. Craik,<sup>58</sup> A. Crocombe,<sup>50</sup> M. Cruz Torres,<sup>1</sup> R. Currie,<sup>52</sup> C. D'Ambrosio,<sup>42</sup> F. Da Cunha Marinho,<sup>2</sup> C. L. Da Silva,<sup>74</sup> E. Dall'Occo,<sup>27</sup> J. Dalseno,<sup>48</sup> A. Danilina,<sup>34</sup> A. Davis,<sup>3</sup> O. De Aguiar Francisco,<sup>42</sup> K. De Bruyn,<sup>42</sup> S. De Capua,<sup>56</sup> M. De Cian,<sup>43</sup> J. M. De Miranda,<sup>1</sup> L. De Paula,<sup>2</sup> M. De Serio,<sup>14,j</sup> P. De Simone,<sup>18</sup> C. T. Dean,<sup>53</sup> D. Decamp,<sup>4</sup> L. Del Buono,<sup>8</sup> B. Delaney,<sup>49</sup> H.-P. Dembinski,<sup>11</sup> M. Demmer,<sup>10</sup> A. Dendek,<sup>30</sup> D. Derkach,<sup>37</sup> O. Deschamps,<sup>5</sup> F. Desse,<sup>7</sup> F. Dettori,<sup>54</sup> B. Dey,<sup>65</sup> A. Di Canto,<sup>42</sup> P. Di Nezza,<sup>18</sup> S. Didenko,<sup>70</sup> H. Dijkstra,<sup>42</sup> F. Dordei,<sup>42</sup> M. Dorigo,<sup>42,k</sup> A. Dosil Suárez,<sup>41</sup> L. Douglas,<sup>53</sup> A. Dovbnya,<sup>45</sup> K. Dreimanis,<sup>54</sup> L. Dufour,<sup>27</sup> G. Dujany,<sup>8</sup> P. Durante,<sup>42</sup> J. M. Durham,<sup>74</sup> D. Dutta,<sup>56</sup> R. Dzhelyadin,<sup>39</sup> M. Dziewiecki,<sup>12</sup> A. Dziurda,<sup>29</sup> A. Dzyuba,<sup>33</sup>



S. Easo,<sup>51</sup> U. Egede,<sup>55</sup> V. Egorychev,<sup>34</sup> S. Eidelman,<sup>38,e</sup> S. Eisenhardt,<sup>52</sup> U. Eitschberger,<sup>10</sup> R. Ekelhof,<sup>10</sup> L. Eklund,<sup>53</sup>  
 S. Ely,<sup>61</sup> A. Ene,<sup>32</sup> S. Escher,<sup>9</sup> S. Esen,<sup>27</sup> T. Evans,<sup>59</sup> A. Falabella,<sup>15</sup> N. Farley,<sup>47</sup> S. Farry,<sup>54</sup> D. Fazzini,<sup>20,42,c</sup> L. Federici,<sup>25</sup>  
 P. Fernandez Declara,<sup>42</sup> A. Fernandez Prieto,<sup>41</sup> F. Ferrari,<sup>15</sup> L. Ferreira Lopes,<sup>43</sup> F. Ferreira Rodrigues,<sup>2</sup> M. Ferro-Luzzi,<sup>42</sup>  
 S. Filippov,<sup>36</sup> R. A. Fini,<sup>14</sup> M. Fiorini,<sup>16,a</sup> M. Firlej,<sup>30</sup> C. Fitzpatrick,<sup>43</sup> T. Fiutowski,<sup>30</sup> F. Fleuret,<sup>7,b</sup> M. Fontana,<sup>22,42</sup>  
 F. Fontanelli,<sup>19,h</sup> R. Forty,<sup>42</sup> V. Franco Lima,<sup>54</sup> M. Frank,<sup>42</sup> C. Frei,<sup>42</sup> J. Fu,<sup>21,l</sup> W. Funk,<sup>42</sup> C. Färber,<sup>42</sup>  
 M. Féo Pereira Rivelto Carvalho,<sup>27</sup> E. Gabriel,<sup>52</sup> A. Gallas Torreira,<sup>41</sup> D. Galli,<sup>15,g</sup> S. Gallorini,<sup>23</sup> S. Gambetta,<sup>52</sup> Y. Gan,<sup>3</sup>  
 M. Gandelman,<sup>2</sup> P. Gandini,<sup>21</sup> Y. Gao,<sup>3</sup> L. M. Garcia Martin,<sup>72</sup> B. Garcia Plana,<sup>41</sup> J. García Pardiñas,<sup>44</sup> J. Garra Tico,<sup>49</sup>  
 L. Garrido,<sup>40</sup> D. Gascon,<sup>40</sup> C. Gaspar,<sup>42</sup> L. Gavardi,<sup>10</sup> G. Gazzoni,<sup>5</sup> D. Gerick,<sup>12</sup> E. Gersabeck,<sup>56</sup> M. Gersabeck,<sup>56</sup>  
 T. Gershon,<sup>50</sup> D. Gerstel,<sup>6</sup> Ph. Ghez,<sup>4</sup> S. Giani,<sup>43</sup> V. Gibson,<sup>49</sup> O. G. Girard,<sup>43</sup> L. Giubega,<sup>32</sup> K. Gizdov,<sup>52</sup> V. V. Gligorov,<sup>8</sup>  
 D. Golubkov,<sup>34</sup> A. Golutvin,<sup>55,70</sup> A. Gomes,<sup>1,m</sup> I. V. Gorelov,<sup>35</sup> C. Gotti,<sup>20,c</sup> E. Govorkova,<sup>27</sup> J. P. Grabowski,<sup>12</sup>  
 R. Graciani Diaz,<sup>40</sup> L. A. Granado Cardoso,<sup>42</sup> E. Graugés,<sup>40</sup> E. Graverini,<sup>44</sup> G. Graziani,<sup>17</sup> A. Grecu,<sup>32</sup> R. Greim,<sup>27</sup>  
 P. Griffith,<sup>22</sup> L. Grillo,<sup>56</sup> L. Gruber,<sup>42</sup> B. R. Gruberg Cazon,<sup>57</sup> O. Grünberg,<sup>67</sup> C. Gu,<sup>3</sup> E. Gushchin,<sup>36</sup> Yu. Guz,<sup>39,42</sup> T. Gys,<sup>42</sup>  
 C. Göbel,<sup>62</sup> T. Hadavizadeh,<sup>57</sup> C. Hadjivasiliou,<sup>5</sup> G. Haefeli,<sup>43</sup> C. Haen,<sup>42</sup> S. C. Haines,<sup>49</sup> B. Hamilton,<sup>60</sup> X. Han,<sup>12</sup>  
 T. H. Hancock,<sup>57</sup> S. Hansmann-Menzemer,<sup>12</sup> N. Harnew,<sup>57</sup> S. T. Harnew,<sup>48</sup> T. Harrison,<sup>54</sup> C. Hasse,<sup>42</sup> M. Hatch,<sup>42</sup> J. He,<sup>63</sup>  
 M. Hecker,<sup>55</sup> K. Heinicke,<sup>10</sup> A. Heister,<sup>10</sup> K. Hennessy,<sup>54</sup> L. Henry,<sup>72</sup> E. van Herwijnen,<sup>42</sup> M. Heß,<sup>67</sup> A. Hicheur,<sup>2</sup>  
 R. Hidalgo Charman,<sup>56</sup> D. Hill,<sup>57</sup> M. Hilton,<sup>56</sup> P. H. Hopchev,<sup>43</sup> W. Hu,<sup>65</sup> W. Huang,<sup>63</sup> Z. C. Huard,<sup>59</sup> W. Hulsbergen,<sup>27</sup>  
 T. Humair,<sup>55</sup> M. Hushchyn,<sup>37</sup> D. Hutchcroft,<sup>54</sup> D. Hynds,<sup>27</sup> P. Ibis,<sup>10</sup> M. Idzik,<sup>30</sup> P. Ilten,<sup>47</sup> K. Ivshin,<sup>33</sup> R. Jacobsson,<sup>42</sup>  
 J. Jalocha,<sup>57</sup> E. Jans,<sup>27</sup> A. Jawahery,<sup>60</sup> F. Jiang,<sup>3</sup> M. John,<sup>57</sup> D. Johnson,<sup>42</sup> C. R. Jones,<sup>49</sup> C. Joram,<sup>42</sup> B. Jost,<sup>42</sup> N. Jurik,<sup>57</sup>  
 S. Kandybei,<sup>45</sup> M. Karacson,<sup>42</sup> J. M. Kariuki,<sup>48</sup> S. Karodia,<sup>53</sup> N. Kazeev,<sup>37</sup> M. Kecke,<sup>12</sup> F. Keizer,<sup>49</sup> M. Kelsey,<sup>61</sup>  
 M. Kenzie,<sup>49</sup> T. Ketel,<sup>28</sup> E. Khairullin,<sup>37</sup> B. Khanji,<sup>12</sup> C. Khurewathanakul,<sup>43</sup> K. E. Kim,<sup>61</sup> T. Kim,<sup>9</sup> S. Klaver,<sup>18</sup>  
 K. Klimaszewski,<sup>31</sup> T. Klimkovich,<sup>11</sup> S. Koliiev,<sup>46</sup> M. Kolpin,<sup>12</sup> R. Kopečna,<sup>12</sup> P. Koppenburg,<sup>27</sup> I. Kostiuk,<sup>27</sup>  
 S. Kotriakhova,<sup>33</sup> M. Kozeiha,<sup>5</sup> L. Kravchuk,<sup>36</sup> M. Kreps,<sup>50</sup> F. Kress,<sup>55</sup> P. Krokovny,<sup>38,e</sup> W. Krupa,<sup>30</sup> W. Krzemien,<sup>31</sup>  
 W. Kucewicz,<sup>29,n</sup> M. Kucharczyk,<sup>29</sup> V. Kudryavtsev,<sup>38,e</sup> A. K. Kuonen,<sup>43</sup> T. Kvaratskheliya,<sup>34,42</sup> D. Lacarrere,<sup>42</sup>  
 G. Lafferty,<sup>56</sup> A. Lai,<sup>22</sup> D. Lancierini,<sup>44</sup> G. Lanfranchi,<sup>18</sup> C. Langenbruch,<sup>9</sup> T. Latham,<sup>50</sup> C. Lazzeroni,<sup>47</sup> R. Le Gac,<sup>6</sup>  
 A. Leflat,<sup>35</sup> J. Lefrançois,<sup>7</sup> R. Lefèvre,<sup>5</sup> F. Lemaitre,<sup>42</sup> O. Leroy,<sup>6</sup> T. Lesiak,<sup>29</sup> B. Leverington,<sup>12</sup> P.-R. Li,<sup>63</sup> T. Li,<sup>3</sup> Z. Li,<sup>61</sup>  
 X. Liang,<sup>61</sup> T. Likhomanenko,<sup>69</sup> R. Lindner,<sup>42</sup> F. Lionetto,<sup>44</sup> V. Lisovskyi,<sup>7</sup> X. Liu,<sup>3</sup> D. Loh,<sup>50</sup> A. Loi,<sup>22</sup> I. Longstaff,<sup>53</sup>  
 J. H. Lopes,<sup>2</sup> G. H. Lovell,<sup>49</sup> D. Lucchesi,<sup>23,o</sup> M. Lucio Martinez,<sup>41</sup> A. Lupato,<sup>23</sup> E. Luppi,<sup>16,a</sup> O. Lupton,<sup>42</sup> A. Lusiani,<sup>24</sup>  
 X. Lyu,<sup>63</sup> F. Machefert,<sup>7</sup> F. Maciuc,<sup>32</sup> V. Macko,<sup>43</sup> P. Mackowiak,<sup>10</sup> S. Maddrell-Mander,<sup>48</sup> O. Maev,<sup>33,42</sup> K. Maguire,<sup>56</sup>  
 D. Maisuzenko,<sup>33</sup> M. W. Majewski,<sup>30</sup> S. Malde,<sup>57</sup> B. Malecki,<sup>29</sup> A. Malinin,<sup>69</sup> T. Maltsev,<sup>38,e</sup> G. Manca,<sup>22,p</sup> G. Mancinelli,<sup>6</sup>  
 D. Marangotto,<sup>21,l</sup> J. Maratas,<sup>5,q</sup> J. F. Marchand,<sup>4</sup> U. Marconi,<sup>15</sup> C. Marin Benito,<sup>7</sup> M. Marinangeli,<sup>43</sup> P. Marino,<sup>43</sup>  
 J. Marks,<sup>12</sup> P. J. Marshall,<sup>54</sup> G. Martellotti,<sup>26</sup> M. Martin,<sup>6</sup> M. Martinelli,<sup>42</sup> D. Martinez Santos,<sup>41</sup> F. Martinez Vidal,<sup>72</sup>  
 A. Massafferri,<sup>1</sup> M. Materok,<sup>9</sup> R. Matev,<sup>42</sup> A. Mathad,<sup>50</sup> Z. Mathe,<sup>42</sup> C. Matteuzzi,<sup>20</sup> A. Mauri,<sup>44</sup> E. Maurice,<sup>7,b</sup> B. Maurin,<sup>43</sup>  
 A. Mazurov,<sup>47</sup> M. McCann,<sup>55,42</sup> A. McNab,<sup>56</sup> R. McNulty,<sup>13</sup> J. V. Mead,<sup>54</sup> B. Meadows,<sup>59</sup> C. Meaux,<sup>6</sup> F. Meier,<sup>10</sup>  
 N. Meinert,<sup>67</sup> D. Melnychuk,<sup>31</sup> M. Merk,<sup>27</sup> A. Merli,<sup>21,l</sup> E. Michielin,<sup>23</sup> D. A. Milanes,<sup>66</sup> E. Millard,<sup>50</sup> M.-N. Minard,<sup>4</sup>  
 L. Minzoni,<sup>16,a</sup> D. S. Mitzel,<sup>12</sup> A. Mogini,<sup>8</sup> J. Molina Rodriguez,<sup>1,r</sup> T. Mombächer,<sup>10</sup> I. A. Monroy,<sup>66</sup> S. Monteil,<sup>5</sup>  
 M. Morandin,<sup>23</sup> G. Morello,<sup>18</sup> M. J. Morello,<sup>24,s</sup> O. Morgunova,<sup>69</sup> J. Moron,<sup>30</sup> A. B. Morris,<sup>6</sup> R. Mountain,<sup>61</sup> F. Muheim,<sup>52</sup>  
 M. Mulder,<sup>27</sup> C. H. Murphy,<sup>57</sup> D. Murray,<sup>56</sup> A. Mödden,<sup>10</sup> D. Müller,<sup>42</sup> J. Müller,<sup>10</sup> K. Müller,<sup>44</sup> V. Müller,<sup>10</sup> P. Naik,<sup>48</sup>  
 T. Nakada,<sup>43</sup> R. Nandakumar,<sup>51</sup> A. Nandi,<sup>57</sup> T. Nanut,<sup>43</sup> I. Nasteva,<sup>2</sup> M. Needham,<sup>52</sup> N. Neri,<sup>21</sup> S. Neubert,<sup>12</sup> N. Neufeld,<sup>42</sup>  
 M. Neuner,<sup>12</sup> T. D. Nguyen,<sup>43</sup> C. Nguyen-Mau,<sup>43,t</sup> S. Nieswand,<sup>9</sup> R. Niet,<sup>10</sup> N. Nikitin,<sup>35</sup> A. Nogay,<sup>69</sup> D. P. O'Hanlon,<sup>15</sup>  
 A. Oblakowska-Mucha,<sup>30</sup> V. Obraztsov,<sup>39</sup> S. Ogilvy,<sup>18</sup> R. Oldeman,<sup>22,p</sup> C. J. G. Onderwater,<sup>68</sup> A. Ossowska,<sup>29</sup>  
 J. M. Otalora Goicochea,<sup>2</sup> P. Owen,<sup>44</sup> A. Oyanguren,<sup>72</sup> P. R. Pais,<sup>43</sup> T. Pajero,<sup>24</sup> A. Palano,<sup>14</sup> M. Palutan,<sup>18,42</sup> G. Panshin,<sup>71</sup>  
 A. Papanestis,<sup>51</sup> M. Pappagallo,<sup>52</sup> L. L. Pappalardo,<sup>16,a</sup> W. Parker,<sup>60</sup> C. Parkes,<sup>56</sup> G. Passaleva,<sup>17,42</sup> A. Pastore,<sup>14</sup> M. Patel,<sup>55</sup>  
 C. Patrignani,<sup>15,g</sup> A. Pearce,<sup>42</sup> A. Pellegrino,<sup>27</sup> G. Penso,<sup>26</sup> M. Pepe Altarelli,<sup>42</sup> S. Perazzini,<sup>42</sup> D. Pereima,<sup>34</sup> P. Perret,<sup>5</sup>  
 L. Pescatore,<sup>43</sup> K. Petridis,<sup>48</sup> A. Petrolini,<sup>19,h</sup> A. Petrov,<sup>69</sup> S. Petrucci,<sup>52</sup> M. Petruzzio,<sup>21,l</sup> B. Pietrzyk,<sup>4</sup> G. Pietrzyk,<sup>43</sup>  
 M. Pikies,<sup>29</sup> M. Pili,<sup>57</sup> D. Pinci,<sup>26</sup> J. Pinzino,<sup>42</sup> F. Pisani,<sup>42,o</sup> A. Piucci,<sup>12</sup> V. Placinta,<sup>32</sup> S. Playfer,<sup>52</sup> J. Plews,<sup>47</sup>  
 M. Plo Casasus,<sup>41</sup> F. Polci,<sup>8</sup> M. Poli Lener,<sup>18</sup> A. Poluektov,<sup>50</sup> N. Polukhina,<sup>70,u</sup> I. Polyakov,<sup>61</sup> E. Polcarpo,<sup>2</sup> G. J. Pomery,<sup>48</sup>  
 S. Ponce,<sup>42</sup> A. Popov,<sup>39</sup> D. Popov,<sup>47,11</sup> S. Poslavskii,<sup>39</sup> C. Potterat,<sup>2</sup> E. Price,<sup>48</sup> J. Prisciandaro,<sup>41</sup> C. Prouve,<sup>48</sup> V. Pugatch,<sup>46</sup>  
 A. Puig Navarro,<sup>44</sup> H. Pullen,<sup>57</sup> G. Punzi,<sup>24,i</sup> W. Qian,<sup>63</sup> J. Qin,<sup>63</sup> R. Quagliani,<sup>8</sup> B. Quintana,<sup>5</sup> B. Rachwal,<sup>30</sup>  
 J. H. Rademacker,<sup>48</sup> M. Rama,<sup>24</sup> M. Ramos Pernas,<sup>41</sup> M. S. Rangel,<sup>2</sup> F. Ratnikov,<sup>37,v</sup> G. Raven,<sup>28</sup> M. Ravonel Salzgeber,<sup>42</sup>



M. Reboud,<sup>4</sup> F. Redi,<sup>43</sup> S. Reichert,<sup>10</sup> A. C. dos Reis,<sup>1</sup> F. Reiss,<sup>8</sup> C. Remon Alepuz,<sup>72</sup> Z. Ren,<sup>3</sup> V. Renaudin,<sup>7</sup> S. Ricciardi,<sup>51</sup>  
 S. Richards,<sup>48</sup> K. Rinnert,<sup>54</sup> P. Robbe,<sup>7</sup> A. Robert,<sup>8</sup> A. B. Rodrigues,<sup>43</sup> E. Rodrigues,<sup>59</sup> J. A. Rodriguez Lopez,<sup>66</sup>  
 M. Roehrken,<sup>42</sup> A. Rogozhnikov,<sup>37</sup> S. Roiser,<sup>42</sup> A. Rollings,<sup>57</sup> V. Romanovskiy,<sup>39</sup> A. Romero Vidal,<sup>41</sup> M. Rotondo,<sup>18</sup>  
 M. S. Rudolph,<sup>61</sup> T. Ruf,<sup>42</sup> J. Ruiz Vidal,<sup>72</sup> J. J. Saborido Silva,<sup>41</sup> N. Sagidova,<sup>33</sup> B. Saitta,<sup>22,p</sup> V. Salustino Guimaraes,<sup>62</sup>  
 C. Sanchez Gras,<sup>27</sup> C. Sanchez Mayordomo,<sup>72</sup> B. Sanmartin Sedes,<sup>41</sup> R. Santacesaria,<sup>26</sup> C. Santamarina Rios,<sup>41</sup>  
 M. Santimaria,<sup>18</sup> E. Santovetti,<sup>25,w</sup> G. Sarpis,<sup>56</sup> A. Sarti,<sup>18,x</sup> C. Satriano,<sup>26,y</sup> A. Satta,<sup>25</sup> M. Saur,<sup>63</sup> D. Savrina,<sup>34,35</sup> S. Schael,<sup>9</sup>  
 M. Schellenberg,<sup>10</sup> M. Schiller,<sup>53</sup> H. Schindler,<sup>42</sup> M. Schmelling,<sup>11</sup> T. Schmelzer,<sup>10</sup> B. Schmidt,<sup>42</sup> O. Schneider,<sup>43</sup>  
 A. Schopper,<sup>42</sup> H. F. Schreiner,<sup>59</sup> M. Schubiger,<sup>43</sup> M. H. Schune,<sup>7</sup> R. Schwemmer,<sup>42</sup> B. Sciascia,<sup>18</sup> A. Sciubba,<sup>26,x</sup>  
 A. Semennikov,<sup>34</sup> E. S. Sepulveda,<sup>8</sup> A. Sergi,<sup>47,42</sup> N. Serra,<sup>44</sup> J. Serrano,<sup>6</sup> L. Sestini,<sup>23</sup> A. Seuthe,<sup>10</sup> P. Seyfert,<sup>42</sup>  
 M. Shapkin,<sup>39</sup> Y. Shcheglov,<sup>33</sup> T. Shears,<sup>54</sup> L. Shekhtman,<sup>38,e</sup> V. Shevchenko,<sup>69</sup> E. Shmanin,<sup>70</sup> B. G. Siddi,<sup>16</sup>  
 R. Silva Coutinho,<sup>44</sup> L. Silva de Oliveira,<sup>2</sup> G. Simi,<sup>23,o</sup> S. Simone,<sup>14,j</sup> N. Skidmore,<sup>12</sup> T. Skwarnicki,<sup>61</sup> J. G. Smeaton,<sup>49</sup>  
 E. Smith,<sup>9</sup> I. T. Smith,<sup>52</sup> M. Smith,<sup>55</sup> M. Soares,<sup>15</sup> I. Soares Lavra,<sup>1</sup> M. D. Sokoloff,<sup>59</sup> F. J. P. Soler,<sup>53</sup> B. Souza De Paula,<sup>2</sup>  
 B. Spaan,<sup>10</sup> P. Spradlin,<sup>53</sup> F. Stagni,<sup>42</sup> M. Stahl,<sup>12</sup> S. Stahl,<sup>42</sup> P. Stefko,<sup>43</sup> S. Stefkova,<sup>55</sup> O. Steinkamp,<sup>44</sup> S. Stemmler,<sup>12</sup>  
 O. Stenyakin,<sup>39</sup> M. Stepanova,<sup>33</sup> H. Stevens,<sup>10</sup> S. Stone,<sup>61</sup> B. Storaci,<sup>44</sup> S. Stracka,<sup>24,i</sup> M. E. Stramaglia,<sup>43</sup> M. Straticiu,<sup>32</sup>  
 U. Straumann,<sup>44</sup> S. Strovkov,<sup>71</sup> J. Sun,<sup>3</sup> L. Sun,<sup>64</sup> K. Swientek,<sup>30</sup> V. Syropoulos,<sup>28</sup> T. Szumlak,<sup>30</sup> M. Szymanski,<sup>63</sup>  
 S. T'Jampens,<sup>4</sup> Z. Tang,<sup>3</sup> A. Tayduganov,<sup>6</sup> T. Tekampe,<sup>10</sup> G. Tellarini,<sup>16</sup> F. Teubert,<sup>42</sup> E. Thomas,<sup>42</sup> J. van Tilburg,<sup>27</sup>  
 M. J. Tilley,<sup>55</sup> V. Tisserand,<sup>5</sup> S. Tolk,<sup>42</sup> L. Tomassetti,<sup>16,a</sup> D. Tonelli,<sup>24</sup> D. Y. Tou,<sup>8</sup> R. Tourinho Jadallah Aoude,<sup>1</sup>  
 E. Tournier,<sup>4</sup> M. Traill,<sup>53</sup> M. T. Tran,<sup>43</sup> A. Trisovic,<sup>49</sup> A. Tsaregorodtsev,<sup>6</sup> G. Tuci,<sup>24</sup> A. Tully,<sup>49</sup> N. Tuning,<sup>27,42</sup> A. Ukleja,<sup>31</sup>  
 A. Usachov,<sup>7</sup> A. Ustyuzhanin,<sup>37</sup> U. Uwer,<sup>12</sup> C. Vacca,<sup>22,p</sup> A. Vagner,<sup>71</sup> V. Vagnoni,<sup>15</sup> A. Valassi,<sup>42</sup> S. Valat,<sup>42</sup> G. Valenti,<sup>15</sup>  
 R. Vazquez Gomez,<sup>42</sup> P. Vazquez Regueiro,<sup>41</sup> S. Vecchi,<sup>16</sup> M. van Veghel,<sup>27</sup> J. J. Velthuis,<sup>48</sup> M. Veltri,<sup>17,z</sup> G. Veneziano,<sup>57</sup>  
 A. Venkateswaran,<sup>61</sup> T. A. Verlage,<sup>9</sup> M. Vernet,<sup>5</sup> M. Veronesi,<sup>27</sup> N. V. Veronika,<sup>13</sup> M. Vesterinen,<sup>57</sup> J. V. Viana Barbosa,<sup>42</sup>  
 D. Vieira,<sup>63</sup> M. Vieites Diaz,<sup>41</sup> H. Viemann,<sup>67</sup> X. Vilasis-Cardona,<sup>40,f</sup> A. Vitkovskiy,<sup>27</sup> M. Vitti,<sup>49</sup> V. Volkov,<sup>35</sup> A. Vollhardt,<sup>44</sup>  
 B. Voneki,<sup>42</sup> A. Vorobyev,<sup>33</sup> V. Vorobyev,<sup>38,e</sup> J. A. de Vries,<sup>27</sup> C. Vázquez Sierra,<sup>27</sup> R. Waldi,<sup>67</sup> J. Walsh,<sup>24</sup> J. Wang,<sup>61</sup>  
 M. Wang,<sup>3</sup> Y. Wang,<sup>65</sup> Z. Wang,<sup>44</sup> D. R. Ward,<sup>49</sup> H. M. Wark,<sup>54</sup> N. K. Watson,<sup>47</sup> D. Websdale,<sup>55</sup> A. Weiden,<sup>44</sup> C. Weissner,<sup>58</sup>  
 M. Whitehead,<sup>9</sup> J. Wicht,<sup>50</sup> G. Wilkinson,<sup>57</sup> M. Wilkinson,<sup>61</sup> I. Williams,<sup>49</sup> M. R. J. Williams,<sup>56</sup> M. Williams,<sup>58</sup>  
 T. Williams,<sup>47</sup> F. F. Wilson,<sup>51,42</sup> J. Wimberley,<sup>60</sup> M. Winn,<sup>7</sup> J. Wishahi,<sup>10</sup> W. Wislicki,<sup>31</sup> M. Witek,<sup>29</sup> G. Wormser,<sup>7</sup>  
 S. A. Wotton,<sup>49</sup> K. Wyllie,<sup>42</sup> D. Xiao,<sup>65</sup> Y. Xie,<sup>65</sup> A. Xu,<sup>3</sup> M. Xu,<sup>65</sup> Q. Xu,<sup>63</sup> Z. Xu,<sup>3</sup> Z. Xu,<sup>4</sup> Z. Yang,<sup>3</sup> Z. Yang,<sup>60</sup> Y. Yao,<sup>61</sup>  
 L. E. Yeomans,<sup>54</sup> H. Yin,<sup>65</sup> J. Yu,<sup>65,aa</sup> X. Yuan,<sup>61</sup> O. Yushchenko,<sup>39</sup> K. A. Zarebski,<sup>47</sup> M. Zavertyaev,<sup>11,u</sup> D. Zhang,<sup>65</sup>  
 L. Zhang,<sup>3</sup> W. C. Zhang,<sup>3,bb</sup> Y. Zhang,<sup>7</sup> A. Zhelezov,<sup>12</sup> Y. Zheng,<sup>63</sup> X. Zhu,<sup>3</sup> V. Zhukov,<sup>9,35</sup>  
 J. B. Zonneveld,<sup>52</sup> and S. Zucchelli<sup>15</sup>

(LHCb Collaboration)

<sup>1</sup>Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

<sup>2</sup>Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

<sup>3</sup>Center for High Energy Physics, Tsinghua University, Beijing, China

<sup>4</sup>Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

<sup>5</sup>Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France

<sup>6</sup>Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

<sup>7</sup>LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

<sup>8</sup>LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France

<sup>9</sup>I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

<sup>10</sup>Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

<sup>11</sup>Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

<sup>12</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

<sup>13</sup>School of Physics, University College Dublin, Dublin, Ireland

<sup>14</sup>INFN Sezione di Bari, Bari, Italy

<sup>15</sup>INFN Sezione di Bologna, Bologna, Italy

<sup>16</sup>INFN Sezione di Ferrara, Ferrara, Italy

<sup>17</sup>INFN Sezione di Firenze, Firenze, Italy

<sup>18</sup>INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>19</sup>INFN Sezione di Genova, Genova, Italy

- <sup>20</sup>*INFN Sezione di Milano-Bicocca, Milano, Italy*
- <sup>21</sup>*INFN Sezione di Milano, Milano, Italy*
- <sup>22</sup>*INFN Sezione di Cagliari, Monserrato, Italy*
- <sup>23</sup>*INFN Sezione di Padova, Padova, Italy*
- <sup>24</sup>*INFN Sezione di Pisa, Pisa, Italy*
- <sup>25</sup>*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- <sup>26</sup>*INFN Sezione di Roma La Sapienza, Roma, Italy*
- <sup>27</sup>*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- <sup>28</sup>*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- <sup>29</sup>*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- <sup>30</sup>*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- <sup>31</sup>*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- <sup>32</sup>*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- <sup>33</sup>*Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
- <sup>34</sup>*Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
- <sup>35</sup>*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
- <sup>36</sup>*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*
- <sup>37</sup>*Yandex School of Data Analysis, Moscow, Russia*
- <sup>38</sup>*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*
- <sup>39</sup>*Institute for High Energy Physics (IHEP), Protvino, Russia*
- <sup>40</sup>*ICCUB, Universitat de Barcelona, Barcelona, Spain*
- <sup>41</sup>*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- <sup>42</sup>*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- <sup>43</sup>*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- <sup>44</sup>*Physik-Institut, Universität Zürich, Zürich, Switzerland*
- <sup>45</sup>*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- <sup>46</sup>*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- <sup>47</sup>*University of Birmingham, Birmingham, United Kingdom*
- <sup>48</sup>*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- <sup>49</sup>*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>50</sup>*Department of Physics, University of Warwick, Coventry, United Kingdom*
- <sup>51</sup>*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>52</sup>*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- <sup>53</sup>*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- <sup>54</sup>*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- <sup>55</sup>*Imperial College London, London, United Kingdom*
- <sup>56</sup>*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- <sup>57</sup>*Department of Physics, University of Oxford, Oxford, United Kingdom*
- <sup>58</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- <sup>59</sup>*University of Cincinnati, Cincinnati, Ohio, USA*
- <sup>60</sup>*University of Maryland, College Park, Maryland, USA*
- <sup>61</sup>*Syracuse University, Syracuse, New York, USA*
- <sup>62</sup>*Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil*  
[associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]
- <sup>63</sup>*University of Chinese Academy of Sciences, Beijing, China*  
[associated with Center for High Energy Physics, Tsinghua University, Beijing, China]
- <sup>64</sup>*School of Physics and Technology, Wuhan University, Wuhan, China*  
[associated with Center for High Energy Physics, Tsinghua University, Beijing, China]
- <sup>65</sup>*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*  
[associated with Center for High Energy Physics, Tsinghua University, Beijing, China]
- <sup>66</sup>*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*  
[associated with LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France]
- <sup>67</sup>*Institut für Physik, Universität Rostock, Rostock, Germany*  
[associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany]
- <sup>68</sup>*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*  
[associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands]
- <sup>69</sup>*National Research Centre Kurchatov Institute, Moscow, Russia*  
[associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]
- <sup>70</sup>*National University of Science and Technology "MISIS", Moscow, Russia*  
[associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]

<sup>71</sup>*National Research Tomsk Polytechnic University, Tomsk, Russia*

*[associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia]*

<sup>72</sup>*Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia-CSIC, Valencia, Spain*

*[associated with ICCUB, Universitat de Barcelona, Barcelona, Spain]*

<sup>73</sup>*University of Michigan, Ann Arbor, USA [associated with Syracuse University, Syracuse, New York, USA]*

<sup>74</sup>*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*

*[associated with Syracuse University, Syracuse, New York, USA]*

<sup>a</sup>Also at Università di Ferrara, Ferrara, Italy.

<sup>b</sup>Also at Laboratoire Leprince-Ringuet, Palaiseau, France.

<sup>c</sup>Also at Università di Milano Bicocca, Milano, Italy.

<sup>d</sup>Also at Università di Modena e Reggio Emilia, Modena, Italy.

<sup>e</sup>Also at Novosibirsk State University, Novosibirsk, Russia.

<sup>f</sup>Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

<sup>g</sup>Also at Università di Bologna, Bologna, Italy.

<sup>h</sup>Also at Università di Genova, Genova, Italy.

<sup>i</sup>Also at Università di Pisa, Pisa, Italy.

<sup>j</sup>Also at Università di Bari, Bari, Italy.

<sup>k</sup>Also at Sezione INFN di Trieste, Trieste, Italy.

<sup>l</sup>Also at Università degli Studi di Milano, Milano, Italy.

<sup>m</sup>Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.

<sup>n</sup>Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

<sup>o</sup>Also at Università di Padova, Padova, Italy.

<sup>p</sup>Also at Università di Cagliari, Cagliari, Italy.

<sup>q</sup>Also at MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines.

<sup>r</sup>Also at Escuela Agrícola Panamericana, San Antonio de Oriente, Honduras.

<sup>s</sup>Also at Scuola Normale Superiore, Pisa, Italy.

<sup>t</sup>Also at Hanoi University of Science, Hanoi, Vietnam.

<sup>u</sup>Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.

<sup>v</sup>Also at National Research University Higher School of Economics, Moscow, Russia.

<sup>w</sup>Also at Università di Roma Tor Vergata, Roma, Italy.

<sup>x</sup>Also at Università di Roma La Sapienza, Roma, Italy.

<sup>y</sup>Also at Università della Basilicata, Potenza, Italy.

<sup>z</sup>Also at Università di Urbino, Urbino, Italy.

<sup>aa</sup>Also at Physics and Micro Electronic College, Hunan University, Changsha City, China.

<sup>bb</sup>Also at School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China.